

- 1 -

**OIL CARRY-OVER PREVENTION FROM HELIUM GAS COMPRESSOR****BACKGROUND**

5 When helium gas is compressed, a relatively large amount of heat is produced. Helium has one of the highest specific heat capacity ratios of known gases ( $\gamma = C_p/C_v = 1.67$  for helium). When helium is compressed, a very effective cooling mechanism must be provided. In the absence of such a cooling mechanism, it would be impossible to reach the temperature of liquefaction of helium, and it would be impossible to produce liquid  
10 helium. In applications such as magneto-resonance imaging (MRI), it is necessary to achieve very low temperatures, of the order of 4-10K. This is currently required to keep superconducting magnets in the superconducting state. Helium is the only known gas which remains gaseous at such temperatures, and accordingly the problems associated with the liquefaction of helium must be tolerated.

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Two alternative methods are known for removing the heat from compressed helium. In one method, helium is compressed in stages, and the compressed gas is cooled after each stage by passing over cooled heat-conductive vanes, for example, water-cooled metallic vanes. In the second method, oil is mixed in with the helium under pressure.  
20 The heat generated by pressurising the helium gas is absorbed by the oil. The oil must be removed from the helium before the helium is used for cooling, since the oil would solidify and cause problems in the cryogenic application if subjected to a temperature in the range of interest, that is, of the order of 4-10K.

25 The present invention relates to the second method of compression and cooling, in which oil is mixed with the helium.

Fig. 1 shows a schematic diagram of a known helium compressor with internal bypass relief valve 12. In cryogenic operations, for example magneto-resonance imaging, it is  
30 common to compress Helium gas using a Helium compressor with internal bypass

- 2 -

relief valve. Such apparatus is manufactured and supplied as a complete unit, with High Pressure (HP) and Low Pressure (LP) ports 16,18. The internal bypass relief valve 12 is provided to prevent damage to the compressor capsule 14, which might otherwise occur if the HP port 16 were blocked, for example. The internal bypass relief valve 12 reacts to an increase in differential pressure between the HP and LP ports by effectively connecting the HP port 16 to the LP port 18. This provides a path 11 for the pressurised helium, and prevents damage to the compressor capsule 14. A non-return valve (NRV) 13 is also typically provided, between the LP port 18 and the internal bypass relief valve connection 15. This is intended to prevent backflow of gas and also to prevent the gases and any contaminants that pass through the bypass relief valve 12 from reaching the LP port 18. Oil separator 17 is provided in the high pressure output line of the compressor capsule 14 to separate the oil from the compressed helium gas. This oil separator may not retain 100% of the oil present in the helium, so it is known to provide an oil adsorber 19, for example of activated charcoal, either within the compressor upstream from the HP port 16, or externally, downstream from the HP port 16.

A known type of helium pump is known as a scroll compressor. Figs 2A-D schematically represent the operative part of a scroll compressor. The scroll compressor comprises two similar, concentric spirals 21, 23, one inserted within the other. Spiral 23 remains stationary as spiral 21 orbits within it. As shown in Fig. 2A, gas is drawn into compression chambers 25, 25' when the outer openings 27, 27' are open. As the spiral 21 orbits, and as shown in Fig. 2B, the outer openings 27, 27' close and the compression chambers 25, 25' are drawn within the spiral 23. As the spiral 21 continues its orbit, and as shown in Fig. 2C, the compression chambers 25, 25' are drawn further into the spiral, and its volume reduces, compressing the gas within the chambers 25, 25'. The outer openings 27, 27' reopen, to expose further compression chambers 29, 29' to the ambient gas. Chambers 25, 25' move towards the centre of the scroll, becoming increasingly compressed until the gas within the chambers reaches maximum pressure at the centre of the compressor, illustrated in Fig. 2D. There, the

- 3 -

high-pressure gas is released through a discharge port 22 in the fixed scroll 23. The various compression chambers 25, 25', 29, 29' etc. arrive sequentially at discharge port 22, while new compression chambers are created by the opening and closing of the outer opening 27.

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While described above as acting to compress gas, in the present application, the scroll compressor will be acting upon a mixture of helium with oil, referred the hereinafter as "gas+oil".

## 10 INTRODUCTION

A typical use for the compressed helium produced by the helium compressor of Fig. 1 is in supplying a pulse tube refrigerator 61 for the cooling of superconductive MRI magnets. A pulse tube refrigerator of known type may be supplied with high pressure  
15 pumped helium gas through an HP line 63 the HP port 16, while a return flow of helium gas at relatively low pressure returns through an HP line 65 to LP port 18. In this context, the HP port typically provides helium gas at a pressure of around 2.4MPa (24bar), while the LP port typically receives gas at a pressure of around 0.6MPa (6bar). Present pulse tube refrigerators typically employ a rotary valve (RV) mechanism 67. A  
20 number of mutually rotating discs define valve opening and closing times, and valve orifice dimension. Such arrangements ensure correct and unchanging timing and dimension relationship between the various valves embodied in the rotary valve mechanism 67. In the present context, both the LP and HP ports would be connected to at least one valve of the rotary valve mechanism.

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The HP and LP ports are typically connected to the pulse tube refrigerator with a relatively long flexible hose 63, 65. During development trials of the applicant's pulse tube refrigerator, it was noticed that some pulse tube refrigerator cold heads with rotary valve and flex lines were flooded with compressor oil over a period of time. As this  
30 occurred on four systems, it could not be considered a random event. Experiments were

- 4 -

performed in order to understand the mechanism of oil carry over. The present invention provides means and methods to overcome or at least alleviate the problems with the prior art compressor / pulse tube refrigerator assembly, and the present invention may be applied to any system in which a helium compressor with internal  
5 bypass relief valve has its HP and LP ports connected to a valve mechanism.

Prior to the present invention, it had been considered that the most likely cause for the presence of oil in the flex tubes was the inefficiency of the adsorber 19 connected to the HP port 16.

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In an initial investigation, as shown in Fig. 1, flex line 65 to the PTR was twenty metres in length. The pressure in the HP line 63 was increased from 2.4MPa (24bar) to 2.9MPa (29bar) in steps of 0.1MPa (1 bar), being run for 4-6 hours for each step. After each step, the two metres of LP line 65 was subjected to residual gas analysis (RGA)  
15 to trace any oil in the line. The flex line under examination line was heated to approximately 200°C. In a line containing oil, very high traces of CO and CO<sub>2</sub> were detected, indicating the breakdown of oil within the tube under examination.

The PTR was run for each trial and showed 10 K no load temperature on its second stage. The PTR was then subjected to heater loads of 40 W and 6 W at its first and  
20 second stages, respectively. However no oil could be traced under any of these conditions. The gas was always able to flow around the gas circuit 63, 67, 65 from the HP port 16 to the LP port 18.

It is known that several fault conditions may cause the rotary valve (RV) 67 to stop,  
25 while the helium compressor continues to operate. In these conditions, the helium pressure inside the HP line rises to a relatively very high value, such as 2.9 MPa (29 bar), while the helium pressure in the low pressure line falls rapidly to a relatively very low pressure, such as 0.15 MPa (1.5bar).

- 5 -

Further investigation was made into the effect of stopping the rotary valve 67 while the compressor was still in operation, after cooling the PTR cold head. As soon as the rotary valve stops, the helium pressure in the HP line 63 and within the connected parts of the compressor increases. The rate and magnitude of this increase depends on the stop position of the rotary valve 67. If the HP port 16 is connected to PTR in the stop position, the pressure increase in the HP line is not very high. This is due to the fact that the complete PTR volume is in line with the compressor. However, if the LP port is connected to the compressor during the rotary valve stop position, the pressure increase in the HP line is very high. As the LP port is connected to the compressor, the gas pressure in the whole LP line is reduced by the compressor to a very low value.

During the investigation rotary valve 67 was stopped in a position which increased the compressor pressure and the pressure in the HP line to 2.8-2.9MPa (28-29bar) and the compressor was run in this condition for 1-2 days. At this point, a small trace of oil could be observed in the two-metre line 33.

However, it was noted that the HP line showed a trace of oil in the line only after a lengthy heating time, while the LP line showed a trace oil almost instantaneously when heated. This unexpected and surprising result led to the conclusion that the oil arriving in the pulse tube refrigerator 61 and the flexible hoses 63, 65 was transferred from the compressor to the LP line first overcoming the NRV (non return valve) resistance and then went to HP line during operation via PTR cold head. This conclusion was tested and led to the present invention, which provides various methods and apparatus for preventing oil from travelling past the NRV and through the LP port.

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A further investigation was performed to trace the mechanism of the oil carry-over. A pressure gauge was connected at position 31, in place of the further adsorber, at the distal end of the two metre LP flex line 33, while the other end was connected to the LP port 18 of the compressor. The HP port 16 of the compressor was kept unattached, and therefore, blocked. The initial pressure in the LP line was 0.15MPa (1.5bar). The

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- 6 -

compressor was run at high HP line pressure of 2.8-2.9MPa (28-29bar) for two to three days. This essentially ran the compressor in an internal bypass condition, with the only gas flow being from the HP line through the internal bypass valve 12 to the LP line. It was found that the pressure in the LP line increased to 0.4MPa (4bar) over a period of 5 time, due to the mixture of gas+oil which travelled through the internal bypass valve 12 without going through the adsorber 19. The gas+oil enters the junction 15. The LP port 18 is at a relatively very low pressure. If the pressure at the junction 15 rises sufficiently, due to the entry of high-pressure gas+oil from the HP line through internal bypass valve 12, it may be possible for some of that gas+oil to travel through the NRV 10 towards and through the LP port 18 into the LP line 65. The two-metre line 33 showed traces of oil when subjected to RGA. This was considered to confirm the hypothesis that gas+oil could cross the NRV. Over a period of time, an appreciable quantity of oil could travel in this way to the LP flex line 65 and then to PTR 61 cold head.

15 To confirm this result, the experiment was repeated with the HP and LP lines 63,65 connected to the PTR 61 and the compressor was started. The rotary valve 67 was then stopped, simulating a fault condition. As soon as the rotary valve 67 stopped, the pressure in the LP line reduced to 0.15-0.2MPa (1.5-2bar) and the pressure in the compressor and the HP line increased to 2.8-2.9MPa (28-29bar). These conditions were 20 similar to those assumed in the earlier experiment, confirming the validity of that experiment.

The present invention resides in part in the finding that oil migration from the compressor to the PTR may be prevented, or at least substantially reduced, by 25 preventing oil carry over from the LP side of the compressor, particularly during stoppage of the rotary valve 67 when the compressor is still in running. In these circumstances, gas+oil travels from the compressor towards the PTR 61 across the NRV 13 due to high pressure difference between the compressor pressure and the low pressure in the LP line 65 of the PTR. This condition should accordingly be avoided

- 7 -

wherever possible. According to a further aspect of the present invention, methods and apparatus are provided to reduce the effect of this condition should it occur.

Accordingly, the present invention provides methods and apparatus as set out in the  
5 appended claims.

The above, and further, objects, advantages and characteristics of the present invention will become apparent from consideration of the following description of certain specific embodiments of the invention, given by way of non-limiting examples only, in  
10 conjunction with the accompanying drawings, wherein:

Fig. 1 shows a known helium compressor supplying compressed helium to a pulse tube refrigerator, according to the prior art;

Fig. 2 shows the action of a scroll compressor, according to the prior art;

15 Fig. 3 shows the system of Fig. 1 adapted according to an embodiment of the present invention;

Fig. 4 shows the system of Fig. 1 adapted according to a further embodiment of the present invention; and

Fig. 5 shows the system of Fig. 1 adapted according to a yet further embodiment of the  
20 present invention.

Fig. 3 shows apparatus, according to an embodiment of the present invention, for preventing oil carry-over from the helium compressor through the low pressure line, comprising an oil trap, known in itself, in a novel and inventive placement, at position  
25 31 within the LP line 65 between the compressor and the rotary valve.

The oil trap is connected to the compressor on the LP line using a two metre flex line 33 on one side and twenty metre flex line 32 on the other end. The initial pressure in flex lines 32, 33 was kept to 0.15MPa (1.5bar). This embodiment was tested by running  
30 the compressor to very high pressure of 2.8-2.9MPa (28-29bar) in internal bypass

- 8 -

mode. It was noticed that the pressure on the gauge increased over a period of time. The compressor was run at a high pressure of about 2.8MPa for several days. The RGA of two-metre line 33 after three days of operation showed contamination with oil, while the twenty metre line 32 beyond the oil trap at position 31 did not show any trace of oil.

5 This test accordingly confirms the satisfactory usage of the oil trap over the given period of time for preventing oil carry over from the helium pump, according to an embodiment of the present invention.

According to a second embodiment of the present invention, a further oil adsorber,

10 similar to oil adsorber 19, is placed in position 31, in substitution for the oil trap discussed above.

According to a third embodiment of the present invention, oil travel from the compressor to the PTR is reduced by placing a gas reservoir in position 31 in the LP

15 line 65 in substitution for the oil adsorber or oil trap discussed above. This reservoir serves to reduce the pressure difference across the NRV 13 in case of the rotary valve stopping. The magnitude of the reduction in pressure difference depends on the volume of the reservoir.

20 Certain known helium compressors such as the SHI and Cryomech compressors are provided with an internal gas reservoir with an adsorber / filter in the LP line. Others, such as the Leybold and APD compressors do not have this feature.

According to a fourth embodiment of the present invention, a combined gas reservoir

25 and oil adsorber is placed in position 31 in the LP line 65. This serves to both prevent and manage the oil carry-over problem. The gas reservoir feature serves to reduce the pressure differential across the NRV, thereby reducing the probability of gas+oil passing through the NRV. The adsorber feature prevents any oil which may pass the NRV from travelling further along the LP line towards the PTR.

- 9 -

According to a fifth embodiment of the present invention, as illustrated in Fig. 4, a low pressure switch 51 is provided in the LP line after the NRV. If the RV 67 stops for any reason, the pressure in the LP line will rapidly drop from its usual 0.5-0.6MPa (5-6bar) level. The switch 51 responds to the lowering of the LP line pressure, and stops the compressor as soon as the lowered pressure is detected. This prevents the build up of a large pressure differential across the NRV 13, and reduces the likelihood of gas+oil travelling through the NRV 13. Since the switch 51 should be designed to react as soon as possible, the switch is preferably designed to react to a relatively small reduction in LP line pressure. For example, the switch may be activated, causing the compressor capsule 14 to stop by a LP line pressure of 0.5MPa (5bar).

The switch 51 may be any pressure sensor capable of operating at the temperatures and pressures likely to be encountered in a helium compressor. In a preferred embodiment, the pressure switch 51 is an electrical switch, and when activated by an unusually low pressure in the LP line, causes a power supply to the compressor capsule to be interrupted, thereby stopping the operation of the compressor.

In a tested embodiment, a pressure switch 51 (a Barksdale Control Products GmbH, UDS 7 type) was fixed on the LP side before LP port 18 of a Leybold helium compressor. The helium compressor had its LP 16 and HP 18 ports connected to a pulse tube refrigerator 61, in this case a 10K OMT PTR 1030207. In order to establish a suitable switching pressure for the pressure switch 51, the low pressure cut off value for the system, which occurs when the PTR is warm, was determined. It was found that with the static charging pressure of 14 bar on the compressor dial gauge, a minimum dynamic pressure of 0.51MPa (5.1bar) and maximum dynamic pressure of 2.4MPa (24bar) were obtained. The pressures changed to 0.63MPa (6.3bar) minimum and 2.2MPa (22bar) maximum in dynamic conditions at lower temperatures with heat loads of 50W at the first stage of the PTR and 6W at the second stage of the PTR. A pressure switch setting of 0.51MPa (5.1bar) was accordingly considered appropriate.

- 10 -

Once the low-pressure switch setting was established, repeated tests were performed to determine the repeatability of the switching of pressure switch 51, and to obtain a suitable turn off delay for the compressor capsule 14. In each test cycle, after the PTR 61 has started to operate, the RV 67 was stopped by turning off the power supply to the RV drive. The pressure switch 51 was set to operate at 0.51MPa (5.1bar). The pressure increase in the HP line and pressure decrease in the LP line were recorded. The time delay from the RV stopping to the compressor stopping was measured. This cycle was repeated five times. In all cases, the compressor stopped within five seconds of the RV stopping. The pressure in the HP line increased to 2.55MPa (25.5bar) maximum. This was insufficient to cause the internal by-pass valve 12 to operate, and any oil to cross the NRV 13. After these tests, the compressor LP port 18 was checked for oil. By visual inspection no oil could be seen. The system further showed no trace of oil or deterioration in performance of the PTR. The test results show that the pressure switch 51 had stopped the compressor almost immediately preventing any possibility of oil carry over from the compressor LP line to the PTR cold head. The switch operating pressure of 0.51 MPa (5.1bar) was found suitable in the tested embodiment. The pressure switch 51 was accordingly demonstrated to operate satisfactorily.

The switch operating pressure should be selected carefully, however. The charging or filling pressure of the PTR should be correct, to maintain correct operation of the pressure switch at the selected switch operating pressure. If the filling static pressure is less than the recommended standard value, or more precisely the value used in determining the pressure switch operating pressure, the compressor may stop during the start up period due to unwanted activation of the pressure switch 51. Also, if the filling static pressure is too high, the time delay required to stop the compressor could be lengthened, and the compressor may go in to bypass mode of operation when the RV stops. This would entail the activation of the internal bypass valve 12, and the possible contamination of the LP line by gas+oil travelling through NRV 13.

- 11 -

According to a sixth embodiment of the present invention, as illustrated in Fig. 6, the internal bypass valve 12 is provided with its own return channel 61 to the compressor capsule 14. In this way, any gas+oil which passes through the internal bypass valve due to excess pressure in the HP line 63, for example, in the case of a stopped rotary 5 valve on an attached equipment 61, will pass directly to the compressor capsule 14, and will not be able to reach the NRV 13 or the LP line 65. Any gas+oil passing through the internal bypass valve 12 will be at a relatively high pressure, much higher than the pressure inside the LP line 65. To prevent the gas+oil from flowing through the compressor capsule 14 into the LP line 65, the return channel 61 is connected to the 10 compressor pump, such as the scroll pump illustrated in Figs. 2A-2D at a relatively high pressure location, closer to the centre of the scrolls than the openings 27, 27' which will receive gas from the LP port 18. The return channel 61 is preferably connected to the compressor by its own manifold, deep in the core of the compressor. Since the helium gas is mixed with oil in the compressor, the fact that the return 15 channel 61 provides gas+oil raises no problems. A disadvantage to this particular embodiment lies in that modifications are required to the compressor capsule.

While the present invention has been explained with reference to a limited number of particular embodiments, numerous alterations and variations may be made to the 20 invention within the scope of the appended claims. Certain of the embodiments may be combined. For example, an oil trap or gas reservoir/absorber may be placed in the LP line upstream from the pressure switch. The present invention maybe usefully applied to any situation in which a helium compressor supplies compressed helium to an equipment through a system of valves. Although the invention has been particularly 25 described with reference to pulse tube refrigerators operated though a rotary valve, it may be usefully applied to any valve controlled equipment.